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METHODS FOR DIAGNOSIS AND TREATMENT OF BLOOM'S SYNDROME

Statement of Government Interest

This invention was made with government support under NIH Grant Nos. HD 04134, CA 50897 and GM 47890. As such, the government has certain rights in this invention.

Background of the Invention

This invention is based upon the discovery by the inventors of the gene associated with Bloom's syndrome ("BS"), the "*BLM* gene" or "*BLM*", and a novel protein encoded by this gene. The discovery of the *BLM* gene and the protein encoded by the gene will have important implications in the diagnosis and treatment of BS, the recognition of carriers of mutations at *BLM*, and more broadly in the development of new cancer diagnostics and therapeutics.

BS is a rare autosomal recessive trait characterized clinically by growth deficiency, a sun-sensitive telangiectatic erythema of the face, immunodeficiency, and male infertility (German, J. Medicine 72:393-406 (1993)). Somatic cells from persons with BS are characterized by a striking genomic instability, and display an increased frequency of chromosome abnormalities (breaks, gaps and rearrangements) and inter- and intramolecular exchanges, including sister-chromatid exchanges (Ray, J.H. and German, J. (1983) The cytogenetics of the "chromosome-breakage syndromes." In: German J. (ed.) Chromosome mutations and neoplasia. Alan R. Liss, New York, pp. 135-168). The hypermutability of BS cells is responsible for the benign and malignant neoplasms in BS patients that arise at unusually early ages and in excessive numbers (German, 1993, supra).

Complementation analyses have established that a single locus, designated *BLM*, is mutated in BS (Weksberg, R., et al. Am. J. Hum. Genet. 42:816-824 (1988)). The *BLM* locus has been assigned to human chromosome 15 (McDaniel, L. D.,

and Schultz, R. A. Proc. Natl. Acad. Sci. USA 89:7968-7972 (1992)), and regionally mapped to chromosome band 15q26.1 based upon tight linkage to *FES* by homozygosity mapping (German, J., et al. Proc. Acad. Natl. Sci. USA 91:6669-6673 (1994)). Prior to the present invention, however, the *BLM* gene had not been identified.

Summary of the Invention

The present invention provides a method for diagnosing BS in a subject comprising detecting the presence of two mutated *BLM* genes or the absence of a wild type BLM gene in nucleic acid of the subject. The present invention also provides a method for determining whether a subject is a carrier of a mutated *BLM* gene comprising detecting the presence of a mutated *BLM* gene in nucleic acid of the subject.

The present invention further provides one or more single-stranded nucleic acid probes which specifically hybridize to the wild type *BLM* gene or the mutated *BLM* gene, and mixtures thereof, which may be formulated in kits, and used for diagnosing BS or determining whether a subject is a carrier of the mutated *BLM* gene.

In addition, the present invention provides an antibody immunoreactive with a wild type BLM protein, as well as an antibody immunoreactive with a mutant BLM protein, which may be formulated in kits, and used for diagnosing BS or determining whether a subject is a carrier of the mutated *BLM* gene.

The present invention also provides a method for treating or preventing the onset of BS in a subject in need of such treatment or prevention comprising the delivery and expression of a functional *BLM* gene into a sufficient number of cells of the subject to treat or prevent the onset of BS in the subject. A stem cell which expresses the *BLM* gene introduced therein through viral transduction, homologous

recombination or transfection is also provided by the invention.

The present invention further provides a recombinant viral vector for treating a defect in the *BLM* gene in a target cell comprising (a) the nucleic acid of or corresponding to at least a portion of the genome of a virus, which portion is capable of directing the infection of the target cell, and (b) a *BLM* gene operably linked to the viral nucleic acid and capable of being expressed as a functional gene product in the target cell.

The present invention still further provides a purified and isolated nucleic acid encoding an enzymatically active BLM protein, a vector comprising this nucleic acid, a cell stably transformed with this vector, as well as a method for producing recombinant, enzymatically active BLM protein. A purified, enzymatically active BLM protein is also provided by the present invention.

Finally, the present invention provides a vector and an embryonic stem cell each of which comprises a mutated *BLM* gene, a non-human, transgenic animal whose germ and somatic cells contain a mutated *BLM* gene sequence introduced into said animal, or an ancestor thereof, at an embryonic stage, as well as a method for producing the non-human, transgenic animal.

Additional objects of the invention will be apparent from the description which follows.

Brief Description of the Figures

Figure 1A represents the genetic map of the *BLM* region of 15q. On the upper horizontal line, the order and distances (shown in kilobase "kb") between the polymorphic microsatellite loci were estimated by long-range-restriction mapping (Straughen, J., et al. Physical mapping of the region containing the Bloom's syndrome gene *BLM* by the identification of YAC and P1 clones from human chromosome 15.

Genomics, 1995, submitted). The distance between *D15S127* and *FES* (not indicated) was determined to be 30 kb by restriction enzyme mapping of a cosmid contig (see below). Vertical lines indicate the position of the marker loci, and the circle represents the centromere. The interval between loci *D15S1108* and *D15S127* is expanded below the map. Vertical lines intersecting mark the unmethylated CpG-rich regions identified by long-range restriction mapping, and arrows indicate the direction of transcription of three genes in the region. Certain YACs, Pls, and cosmids (Y, P, and c, respectively) from the contig (Straughen, et al., supra) are depicted by horizontal lines underneath the map. Dashes on the YAC lines indicate internal deletions. At the top of the figure, the horizontal cross-hatched bars indicate regions proximal to *BLM* that remained heterozygous in the low-SCE LCLs and regions distal to *BLM* that had become homozygous. The minimal region to which *BLM* was thus assigned by SCP mapping is represented in black.

Figure 1B represents the autoradiographic evidence showing heterozygosity proximal to *BLM* and reduction to homozygosity distal to *BLM*. The four persons of five from whom low-SCE LCLs had been established that were informative at *D15S1108* or *D15S127* are shown. To determine both the constitutional and the recombinant cell line genotypes, PCRs were carried out using DNA samples prepared from high-SCE cells (P^h) and low-SCE LCLs (P^l) of persons with BS as well as samples from their fathers (PF) and their mothers (PM). These persons are identified by their Bloom's Syndrome Registry designations (see German, J., and Passarge, E. Clin. Genet. 35:57-69 (1989)). Arrows point to DNA fragments amplified from the heterozygous alleles of the constitutional genotypes, pat (for paternal) and mat (for maternal). Asterisks mark alleles in the low-SCE LCLs that are lost through somatic crossing-over. Lines mark DNA fragments amplified from alleles of the parents but that were not

transmitted to the offspring with BS. From one of the four persons with BS, 11 different clonal LCLs were examined; 3 of the 11 had undergone reduction to homozygosity at loci distal to *BLM* -- as explained elsewhere ((Ellis, N. A., et al. Somatic intragenic recombination within the mutated locus *BLM* can correct the high-SCE phenotype of Bloom syndrome cells. Am. J. Hum. Genet., 1995, in press). Autoradiographic patterns are shown from 2 of the 11 low-SCE LCLs from 11(IaTh), one representative of cell lines in which allele losses were detected (P^1 sample on right) and another of cell lines in which they were not (P^1 sample on left).

Figure 2 is depictive of the 4,437-bp H1-5′ sequence, which represents the merged sequences of the H1 cDNA and the 5′ clones, with its encoded 1,417-residue amino acid sequence (single-letter code). Nucleotides in the open reading frame starting at the first in-frame ATG, 75 bp from the first nucleotide of the H1-5′ sequence, are capitalized. The in-frame nonsense codon (TAA) marked by a period is followed by 88 nucleotides of 3′ untranslated sequence. At the initiator methionine, there is a Kozak consensus sequence (Kozak, M. J. Cell Biol. 108:229-241 (1989)), and an acceptable polyadenylation sequence (underlined) is present 20-bp upstream of a 21-bp polyA tail. Sites at which substitution or deletion were detected in persons with BS (see Table 1) are boxed, and a site at which an insertion was identified is marked by a diamond. The *Eag*I and *Sma*I sites used in the construction of a full-length cDNA referred to as B3 (see Experimental Details Section) are overlined. Asterisks mark amino acid identities to three motifs present in the RNA polymerase II largest subunit.

Figure 3 is depictive of the nucleotide sequence of the 5′ end of the candidate gene determined by cDNA analysis and 5′-RACE experiments. The sequence of the longest cDNA isolated (clone R1) is shown. The sequences were obtained by analysis of 11 lymphoblastoid cDNAs (clone names prefixed by

an R), identified by screening 8 x 10^6 clones with a *EagI/SmaI* DNA fragment from the 5′ part of the H1-5′ sequences (Fig. 2), and of 12 5′-RACE clones amplified from fibroblast cDNA with nested PCR primers (Experimental Details Section). Vertical lines mark the nucleotides at which nine lymphoblastoid cDNA (clones named above the sequences) and six cloned 5′-RACE fragments (clones named below the sequences) initiated. Three cDNA and six 5′-RACE clones not shown contained sequences which initiated less than 38 bp upstream of the first in-frame ATG. The sequences at the 5′ end are G+C-rich (71%), perhaps explaining the absence of in-frame nonsense codons upstream of the first in-frame ATG.

Figure 4 represents the amino acid sequence homologies in the seven conserved helicase domains between the putative peptide encoded by the H1-5′ sequence and by the three other known members of the RecQ subfamily of helicases. The numbers (left) indicate amino acid positions in each peptide, and gene product names are at the right. Sequence alignments were performed by the Megalign computer program (DNAStar); dashes indicate gaps inserted by the program to maintain alignment. Amino acid residues that are identical at a position between sequences are shaded. Two different shadings are used when at a position two pairs of identical amino acids were observed. Overlined sequences mark the seven helicase domains (Gorbalenya, A. E., et al. Nucl. Acids Res. 17:4713-4730 (1989)). The DExH box is in helicase domain II. Asterisks denote positions at which putative missense mutations were identified. The candidate gene product is referred to here as *BLM* because mutations have been discovered in the gene in persons with BS (see text).

Figures 5A and 5B represent the Northern analysis of the H1-5′ sequences expressed in cultured cells. In Figure 5A, RNA preparations were analyzed from HG2162, a normal LCL; HG2635, a normal diploid fibroblast cell line; and HeLa cells. In Figure 5B, RNA preparations were analyzed

from HG 1943 and HG2162 -- normal LCLs -- and HG2703, HG1584, HG1987, HG1972, HG2231, HG1626, HG2820 -- BS LCLs. Thirty micrograms of total RNA from each cell line was loaded in each lane. Labeled probes -- the H1 cDNA (upper panels) and a cDNA for G3PDH (lower panels) -- were hybridized to membranes of the blotted gels and, after washing, the membranes were exposed from one to three days (Figure 5A) or for 15 minutes (Figure 5B). On a 7-day exposure, faint bands resembling the hybridization pattern in normal cells were detected at the 4.5-kb position in HG2703, HG1584, and HG2820. The LCLs developed from persons with BS are shown in Table 1, except HG2703, [NR2(CrSpe)]; and HG2820, [142(MaMatu)].

Figures 6A-6E represent the novel SSCP conformers detected in cDNA samples isolated from BS LCLs after PCR-amplification of the *BLM* gene. Each figure includes five lanes of cDNAs from five unrelated persons with BS amplified with oligonucleotides designed from a unique region of the *BLM* gene. The novel conformers in which mutations were detected are shown in the center lanes of each figure: 6A, BS LCL HG1514 from 15(MaRo); 6B, BS LCL HG1624 from 113(DaDem); 6C, BS LCL HG1926 from 97(AsOk); 6D, BS LCL HG2231 from 139(ViKre); 6E, BS LCL HG1626 from 93(YoYa). Not shown are novel conformers in 92(VaBi) and 112(NaSch).

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Detailed Description of the Invention

The present invention provides a method for diagnosing BS in a subject comprising detecting the presence of two mutated *BLM* genes or the absence of a wild type BLM gene in nucleic acid of the subject. The present invention also provides a method for determining whether a subject is a carrier of a mutated *BLM* gene comprising detecting the presence of a mutated *BLM* gene in nucleic acid of the subject.

As used herein, the "mutated *BLM* gene" is the mutated form of the normal *BLM* gene, which contains one or more deletion, insertion, point or rearrangement mutations, or a combination thereof, that may result in loss or alteration of activity of the gene product expressed by the mutated *BLM* gene. A subject who inherits a copy of the mutated *BLM* gene on each chromosome 15 has clinical BS. The "wild type *BLM* gene" is the normal form of the gene which expresses an enzymatically active gene product. The wild type *BLM* gene is present in subjects who are not carriers of the mutated *BLM* gene, and is the preferentially expressed gene in subjects who are carriers of the mutated *BLM* gene.

The methods of the present invention may be used to determine whether persons in the population at large are carriers of the mutated *BLM* gene or have BS, for identifying persons at risk in developing the disease, i.e. relatives of persons with BS, as well as for confirming diagnosis of BS. The methods of the present invention are also useful for identifying couples who are carriers of the mutated *BLM* gene and thus at risk for propagating offspring who will have BS, as well as for identifying embryos or fetuses which may be born with BS. Accordingly, as used herein, "subject" may be an embryo, fetus, newborn, infant or adult.

The presence of the mutated *BLM* gene(s) (or the absence of the wild type *BLM* gene) may be detected by procedures known in the art including but not limited to standard sequencing techniques (e.g. dideoxy chain termination), restriction enzyme digestion analysis, hybridization with one or more probes hybridizable to the mutated and/or wild type *BLM* gene using standard procedures such as Southern blot analysis, polymerase chain reaction using sense and antisense primers prepared from the mutated and/or wild type *BLM* genes, and combinations thereof.

The presence of the mutated *BLM* gene(s) (or the absence of the wild type *BLM* gene) also may be detected by

detecting expression of the gene product of the gene. Such expression products include both mRNA as well as the protein product itself. mRNA expression may be detected by standard sequencing techniques, hybridization with one or more probes hybridizable to the mutated and/or wild type *BLM* mRNA using standard procedures such as Northern blot analysis, dot and slot hybridization, S1 nuclease assay, or ribonuclease protection assays, polymerase chain reaction using sense and antisense primers prepared from the mutated and/or wild type *BLM* genes, and combinations thereof. The protein may be detected using antibodies to the protein expressed by the mutated *BLM* gene and/or the wild type *BLM* gene by procedures known in the art including but not limited to immunoblotting, immunoprecipitation, solid phase radioimmunoassay (e.g. competition RIAs, immobilized antigen or antibody RIAs, or double antibody RIAs), enzyme-linked immunoabsorbent assay, and the like.

The present invention also provides single-stranded nucleic acid probes and mixtures thereof for use in diagnosing BS and/or determining whether an individual is a carrier of the mutated *BLM* gene. The nucleic acid probes may be DNA, cDNA, or RNA, and may be prepared from the mutated and/or wild type *BLM* gene. The probes may be the full length sequence of *BLM* gene, or fragments thereof. Typical probes are 12 to 40 nucleotides in length. Generally, the probes are complementary to the *BLM* gene coding sequences, although probes to introns are also contemplated. The probes may be synthesized using an oligonucleotide synthesizer such as Applied Biosystems Model 392 DNA/RNA synthesizer, and may be labeled with a detectable marker such as a fluorescence, enzyme or radiolabeled markers including ^{32}P and biotin, and the like. Combinations of two or more labelled probes corresponding to different regions of the *BLM* gene also may be included in kits to allow for the detection and/or analysis of the *BLM* gene by hybridization.

The present invention also provides antibodies immunoreactive with the protein expressed by the wild type *BLM* gene (and analogues thereof), as well as antibodies immunoreactive with the protein expressed by the mutated *BLM* gene. The antibodies may be polyclonal or monoclonal and are produced by standard techniques. The antibodies may be labeled with standard detectable markers (e.g. chemiluminescent detection systems and radioactive labels such as ^{125}I) for detecting the wild type and mutated *BLM* genes. The antibodies also may be presented in kits with detectable labels and other reagents and buffers for such detection.

The present invention also provides a method for treating or preventing the onset of BS in a subject in need of such treatment or prevention comprising the delivery and expression of a functional *BLM* gene into a sufficient number of cells of the subject, preferably bone marrow stem cells, to treat or prevent the onset of BS in the subject. As used herein, "functional *BLM* gene" is a gene which when incorporated into a cell's nucleic acid expresses a functional gene product, and includes the wild type *BLM* gene as well as variations thereof. The delivery and expression of the functional *BLM* gene may be accomplished by introducing the functional *BLM* gene into the cells or by correcting the mutation(s) in the subject's *BLM* gene.

The functional *BLM* gene may be delivered into the subject's cells by a number of procedures known to one skilled in the art, e.g. electroporation, DEAE dextran, cationic liposome fusion (using both monocationic and polycationic lipids), protoplast fusion, DNA coated microprojectile bombardment, injection with recombinant replication-defective retroviruses, homologous recombination, and the like. Accordingly, a stem cell which expresses the *BLM* gene introduced therein through viral transduction,

homologous recombination, or transfection is also provided by the present invention.

The present invention also provides a recombinant viral vector for treating a defect in the *BLM* gene in a target cell comprising (a) the nucleic acid of or corresponding to at least a portion of the genome of a virus, which portion is capable of directing the infection of the target cell, and (b) a functional *BLM* gene operably linked to the viral nucleic acid and capable of being expressed as a functional gene product in the target cell. The recombinant viral vectors of the present invention may be derived from a variety of viral nucleic acids known to one skilled in the art, e.g. the genomes of HSV, adenovirus, adeno-associated virus, Semiliki Forest virus, vaccinia virus, and other retroviruses or DNA viruses.

In addition, the present invention provides a purified and isolated nucleic acid encoding an enzymatically active BLM protein, which may be the wild type protein or an analogue thereof, and includes all nucleic acid sequences encoding such enzymatically active proteins, including substitutions due to the degeneracy of the genetic code. The nucleic acid may be genomic DNA, cDNA or RNA. In the preferred embodiment, the nucleic acid encodes the amino acid sequence contained in Figure 2. In the particularly preferred embodiment, the nucleic acid has the nucleotide sequence contained in Figure 2.

The present invention also provides a vector comprising nucleic acid encoding an enzymatically active BLM protein, as well as a cell stably transformed with the vector. The vector may be any plasmid, viral-derived nucleic acid, lytic bacteriophage derived from phage lambda, cosmid, filamentous single-stranded bacteriophage such as M13, and the like, for cloning nucleic acid or introducing the nucleic acid into a cell for expression. The cell may be eukaryotic or prokaryotic. Suitable host cells include but are not

limited to bacterial cells such as E. coli, Bacillus subtilis, Agrobacterium tumefaciens, Bacillus subtilis, Agrobacterium tumefaciens, Bacillus megaterium, eukaryotic cells such as Pichia pastoris, Chlamydomonas reinhardtii, Cryptococcus neoformans, Neurospora crassa, Podospora anserina, Saccharomyces cerevisiae, Saccharomyces pombe, Uncinula necator, cultured insect cells, cultured chicken fibroblasts, cultured hamster cells, cultured human cells such as HT1080, MCF7, 143B and cultured mouse cells such as EL4 and NIH3T3 cells. Such expression systems may be used to produce a recombinant, enzymatically active BLM protein by culturing a cell transformed with a vector comprising a nucleic acid encoding an enzymatically active BLM protein, and recovering BLM protein from the culture.

The present invention also provides a purified enzymatically active BLM protein. The protein may be the wild type protein or an analogue thereof. As used herein, "analogue" means functional variants of the wild type protein, and includes BLM proteins isolated from mammalian sources other than human, as well as functional variants thereof. The protein also may be isolated from native cells or recombinantly produced. Preferably, the protein has the amino acid sequence contained in Figure 2.

The present invention also provides a vector for use in preparing a non-human, transgenic animal comprising a mutated *BLM* gene which is capable of introducing the mutated *BLM* gene in at least some embryonic cells to which the vector is introduced, an embryonic stem cell comprising a mutated *BLM* gene which has been integrated into the cell following transduction with the vector above, as well as a non-human transgenic animal of BS which would be useful for studying BS as well as cancer in general. The mutated *BLM* gene may be integrated into the germ line of a non-human animal such as a mouse, rat, goat, sheep or other non-human species in order to obtain a transgenic animal model by methods known in the

art (see Alberts, B., et al. Molecular Biology of the Cell, 2d. Garland Publ. Inc., New York and London, pp. 267-269 (1989)). For example, nucleic acid encoding the mutated BLM protein can be inserted into the genome of a replication-defective virus such as HSV or a retrovirus or transposen and the resultant construct injected into embyronic stem cells. Alternatively, the transgenic animal may be made by injecting nucleic acid into the male pronucleus of a fertilized egg of a nonhuman animal, transplanting the "transgenic embryo" into a pseudopregnant female and then analyzing offspring for the presence of the injected nucleic acid in their genome.

Based upon the high incidence of a variety of tumors in a variety of tissues in a BS patient which appears to model cancer development in the general population (German, J. Medicine 72:393-406 (1993)), the identification of the *BLM* gene and its gene product should be useful for developing diagnostics and therapeutics for cancer in the population at large.

The present invention is described in the following Experimental Details Section, which is set forth to aid in an understanding of the invention, and should not be construed to limit in any way the invention as defined in the claims which follow thereafter.

Experimental Details Section

I. Materials and Methods

A. Subjects and Samples

The persons with BS in whom low-SCE lymphocytes have arisen were described previously (German, J., et al. Bloom's syndrome. XIX. Cytogenetic and population evidence for genetic heterogeneity. Clin. Genet., 1995, in press). Epstein-Barr virus transformed lymphoblastoid cell lines (LCLs) were developed from these and other persons with BS by standard culture methods using material obtained through the Bloom's Syndrome Registry (German and Passarge, supra). The

recombinant low-SCE LCLs in which reduction to homozygosity had been detected, and the cells used to determine the constitutional genotypes of the five persons from whom these recombinant low-SCE LCLs were developed, also have been described (Ellis, et al. Am. J. Hum. Genet., 1995, supra). The polymorphic loci typed included some previously reported (Beckmann, J.S., et al. Hum. Mol. Genet. 2:2019-2030 (1993); Gyappay, G., et al. Nature Genetics 7:246-339 (1994)) and others that were identified during the physical mapping of the *BLM* region of chromosome 15 (Straughen, et al., supra). The methods of preparation of DNA samples, oligonucleotide primers, and conditions for PCR amplification of microsatellite polymorphisms on chromosome 15 have been described (German, et al., 1994, supra; Ellis, N.A., et al. Am. J. Hum. Genet. 55:453-460 (1994); Straughen, et al., supra).

B. Direct cDNA Selection

Direct cDNA selection was carried out as described by Parimoo, S., et al. (Proc. Natl. Acad. Sci. USA 88:9623-9627 (1991)). Briefly, DNAs (15 ng) from commercial lambda cDNA libraries prepared from cultured foreskin fibroblasts (Clontech) and Jurkat cells (Stratagene) were amplified by PCR (94°C 1 min, 55°C 1 min, 72°C 2 min and 10 sec for 32 cycles) using primer set A (GGTGGCGACGACTCCTGGA and ACCAGACCAACTGGTAATG) for the fibroblast cDNA library and the universal forward and reverse M13 sequencing primers for the Jurkat cDNA library under standard conditions with *Taq* polymerase (Boehringer Mannheim). *Eco*RI-digested cosmid (c905) or P1 (P1958) DNAs (100 ng) bound to Hybond N membrane in 10 X SSC, were denatured in 0.5 M NaOH/1.5 M NaCl, neutralized in 0.5 M Tris-HCl pH 7.2/1.5 M NaCl, and fixed by UV-crosslinking. Hybridization of the PCR-amplified cDNAs to repetitive sequences on the cosmid and P1 clones was blocked by prehybridizing the membranes with Cot1 DNA (25 ng/m;

Gibco, BRL), poly(dI):poly(dC) (20 ng/μl; Pharmacia), vector DNA (pWE15 or pAD10SacBII at 25 ng/μl in 5 X SSPE, 5 X Denhardt's solution, and 0.5% SDS at 65°C overnight. Hybridization of the PCR-amplified cDNAs (25 ng/μl) was at 65°C for 2 days in the same solution without poly(dI):poly(dC). The membranes were washed, and without elution the bound cDNAs were amplified by PCR with primer set A, followed by nested PCR with primer set B (ATGGTAGCGACCGGCGCTCA and CCGTCAGTATCGGCGGAATT) for the fibroblast library and the T3 and T7 sequencing primers for the Jurkat library. A sample of the PCR product after each amplification was analyzed by agarose gel electrophoresis, and another was cloned into Bluescript. Independent clones were picked at random, plasmid DNAs prepared, and insert sizes were determined by restriction enzyme digestion and agarose gel electrophoresis. Inserts from selected clones were purified and used as hybridization probes against all of the other clones as well as against selected genomic DNAs to determine the chromosomal origin of the sequences (see below). The enrichment procedure was repeated and the selected cDNA clones analyzed again. The fibroblast cDNA clone 905-28 was obtained after two rounds of selection (250,000-fold enriched), and was sequenced by the dideoxy chain-termination technique (Sanger, F., et al. Proc. Natl. Acad. Sci. 74:55463-5467 (1977); Tabor, S., and Richardson, C.C. Proc. Natl. Acad. Sci. USA 84:4767-4771 (1987)).

The genomic origin of clones isolated by direct selection were verified by hybridization of inserts to Southern blots of DNAs from the following: clones in the contig; human cells; and two human x hamster somatic cell hybrids, one of which contains an intact chromosome 15 as the only human chromosome present (GS89K-1; Warburton, D., et al. Genomics 6:358-366 (1990)) and one in which the only chromosome 15 material present had, through a translocation, lost all the sequences distal to band 15q25 (GM10664,

obtained from NIGMS Human Genetic Mutant Cell Repository at the Cornell Institute of Medical Research).

C. cDNA Cloning, 5′-RACE, and cDNA Sequencing

The selected cDNA 905-28 was hybridized to 10^6 clones from a HeLa cDNA library (Stratagene) according to standard procedures (Sambrook, J., Fritsch, E. F., and Maniatis, T. (1989) Molecular Cloning. A Laboratory Manual. 2nd edition, Cold Spring Harbor University Press). Twenty-eight lambda clones were isolated and converted to Bluescript plasmids by superinfection with ExAssist helper phage (Stratagene). DNA was prepared and 15 independent size-classes of clones were identified. The 5′-end of a clone from each class was sequenced with Bluescript SK sequencing primer. To extend the sequence, two oligonucleotides were synthesized from the beginning and the end of each of the 5′ sequences, and sequencing was performed on the largest cDNA clone obtained by hybridization (clone H1). This procedure provided sequences from both DNA strands for most of the H1 cDNA. Ambiguous segments were determined by sequencing with specific oligonucleotides.

Because the reading frame was open at the 5′ end of the H1 clone, additional upstream sequences were obtained by a PCR method. PCR was carried out on DNA prepared from the HeLa cDNA library using an oligonucleotide (Y177, TTGTGGTGTTGGGTAGAGGTT) 8 bp from the 5′ end of H1 and the T3 sequencing primer. The PCR products were cloned into pT7Blue (Novagen), 18 clones were isolated, and the 8 largest inserts were sequenced. The three largest of these clones (5′-5, 5′-15, and 5′-17) extended the sequences 289 bp 5′ of the H1 cDNA. The complete cDNA sequences present in the HeLa library are referred herein as H1-5′ (Fig. 2). Database searches then were carried out according to the method of Altschul, S.F., et al. (J. Mol. Biol. 215:403-410 (1990)) using segments of the predicted amino acid sequence encoded

in the HI-5′ sequence as queries against the collected amino acid sequence databases that are accessible through the National Library of Medicine.

A full-length clone referred to as B3 was constructed by performing PCR of HeLa library DNA using an oligonucleotide (Y180, GCCGCCGGCACCAAC) from the 5′ end of the H1-5′ sequence and an internal oligonucleotide (BC13, CCTCAGTCAAATCTATITGCTC) which permitted amplification of a 739-bp product. *Eag*I and *Sma*I sites (Fig. 2) were used to clone the product into *Not*I/*Sma*I-digested H1 DNA.

The 461-bp *Eag*I/*Sma*I fragment of B3 was isolated and used to probe 8 x 10^6 clones of a pREP4-cloned unidirectional cDNA library from DEB-treated lymphoblastoid cells (Strathdee, C. A., et al. Nature 356:763-767 (1992)). Twelve cDNA clones were identified, and the 5′ end of 11 were sequenced. Eight of them are apparently full-length cDNAs (Fig. 3). By restriction enzyme analysis, 1 of the 12 clones was shown to contain a deletion 3′ of nucleotide 2897 and the insertion of about 250 bp there.

5′-RACE (rapid amplification of cDNA ends) was performed to characterize the 5′ sequences of the candidate gene using a Clontech Marathon™ cDNA Amplification Kit according the manufacturers specifications. Briefly, first-strand synthesis was carried out with MMLV reverse transcriptase using polyT-primed RNAs prepared from cultured fibroblast, lymphoblastoid, and HeLa cells and polyA+ RNA from placenta (provided in the kit). Then, second-strand synthesis was performed with RNAseH, *E. coli* PoLI, and *E. coli* DNA ligase. The DNA ends were made blunt with T7 DNA polymerase, and adapters with overhanging ends were ligated to the cDNA. Nested PCRs then were carried out using 5′ oligonucleotides from the adaptor (AP1 and AP2) and internal 3′ oligonucleotides from the H1-5′ sequence (BC5, GCCATCACCGGAACAGAAGGAAA; and BC11, TCTTCTGGAGAAGGTGGAACAA). Bands derived from the H1-5′ sequences were identified in all

four of the cDNA samples. PCR products from the 5′-RACE-amplified fibroblast cDNA was cloned into Bluescript, and the 5′ ends of 12 clones were sequenced (Fig. 3).

D. Northern Blot Analysis

RNAs were prepared from cultured cells using TRIzol reagent (Gibco, BRL) according to the manufacturer's instructions. Total RNAs (30 μg) were size-separated by electrophoresis through 6.3% formaldehyde 1.2% agarose gels in 0.02 M MOPS, 0.05 M sodium acetate pH 7.0, and 0.001 M EDTA. The RNAs were transferred to Hybond-N (Amersham) in 20 X SSPE and fixed to the membranes by UV-crosslinking. Hybridizations were performed as described (Ellis, N. A., et al. Nature Genetics 6:394-400 (1994)).

E. Single-Strand Conformation Polymorphism (SSCP) Analysis

After first-strand synthesis, PCR was carried out with 200 ng cDNA, 5.2 pmol of each oligonucleotide primer (Table 2), 3% DMSO, 0.2 mM dNTPs (Pharmacia), 1 X reaction buffer from Boehringer Mannheim, 0.25 units of Taq polymerase (Boehringer Mannheim), and 1.0 μCi of α-[^{32}P]-dCTP in a total volume of 10 μl. Each reaction was overlaid with mineral oil and initially denatured for 5 min at 94°C followed by 35 cycles of 94°C for 1 min, 60°C for 1 min, and 72°C for 1 min. The last cycle was extended at 72°C for 5 min. PCR products were diluted in 25 μl of 0.1% SDS, 10 mM EDTA and 25 μl of 95% formamide, 20 mM EDTA, 0.5% bromophenol blue, and 0.5% xylene cyanol. Two conditions for electrophoresis were carried out for each set of reactions. In one, electrophoresis of a 90 mM Tris borate, 2 mM EDTA (pH 7.5) (Gibco, BRL), 35% MDE (AT Biochem) 10% glycerol gel was performed at room temperature, cooled by fans; in the other, electrophoresis of a 90 mM Tris borate, 2 mM (Gibco, BRL), 25% MDE (AT Biochem) gel was performed at 4°C.

Electrophoresis was carried out for both conditions at 40W constant power in 0.6 X TBE running buffer. After electrophoresis, gels were transferred to 3MM paper and dried on a vacuum slab dryer. Autoradiography overnight with Kodak XAR5 film without intensifying screens was sufficient to detect bands.

F. DNA Sequencing of SSCP Conformers

Isolation of DNA from SSCP conformers was performed as described previously in Groden et al. (Cell 66:589-600 (1991); Am. J. Hum. Genet. 52:263-272 (1993)). Each sample was analyzed by agarose gel electrophoresis to confirm the correct size. The remainder of each sample was purified using Centricon 100 columns (Amicon) and sequenced using the dsDNA Cycle Sequencing System (Gibco, BRL) with the forward primer originally designed for SSCP analysis. Sequencing reactions were analyzed by electrophoresis through 5% denaturing polyacrylamide gels. Gels were dried and exposed to Hyperfilm-MP (Amersham) without intensifying screens.

II. Results

A. Localization of *BLM* to a 250-kb Interval

BLM previously was localized by SCP mapping to a 1.3 cM interval bounded proximally by *D15S116* and distally by four tightly linked loci *D15S127*, *FES*, *D15S158*, and *IP15M9* (Ellis, et al., Am. J. Hum. Genet., 1995, supra). The four loci are present in a 1-2 cM interval on chromosome 15 (Beckmann, et al., supra; Gyappay, et al., supra). The order of these four loci was determined by PCR analysis of clones in a 2-Mb YAC and P1 contig that encompasses *BLM* (Straughen, et al., supra). The four loci were oriented with respect to the telomere by finding a recombinant chromosome in a BS family in which crossing-over had occurred between *BLM* and *IPI5M9*, placing *IPI5M9* on the distal end of the contig (Fig. 1A). Because *D15S127* was the most proximal locus that was

reduced to homozygosity in low-SCE LCLs, polymorphic loci in the region proximal to it were sought. There, a polymorphic locus, *D15S1108*, was identified that remained constitutionally heterozygous in the recombinant low-SCE LCLs, in contrast to locus *D15S127* that had become homozygous in them (Fig. 1B). This shift from heterozygosity to homozygosity of markers indicated that *BLM* is situated in the 250-kb region between *D15S1108* and *D15S127*.

Two genes, *FES* and *FUR*, map distal to *D15S127* in this region of chromosome 15. SCP mapping thereby eliminated them as candidates for *BLM*. Consistent with this conclusion, an earlier mutation search in six BS LCLs had failed to uncover mutations in *FUR* (data not shown).

B. Isolation of a Candidate for BLM

cDNAs were isolated from the 250-kb region between *D15S1108* and *D15S127* by direct cDNA selection using cDNA libraries from cultured fibroblasts and the T-cell line Jurkat. Libraries from these cell lines were chosen because fibroblasts and T lymphocytes from persons with BS exhibit the high-SCE phenotype, indicating that *BLM* is expressed in these cell types. In direct selection experiments using cosmid c905 (see Fig. 1A), an 847-bp cDNA designated 905-28 was isolated after two rounds of direct selection. It was found in less than 1 in 1 x 10^6 clones screened in the fibroblast library but was present in 6 of 28 selected cDNA clones, a 250,000-fold enrichment. The six cDNAs represented by 905-28 were the only selected cDNAs that by Southern analysis mapped to the *BLM* region and that identified non-repetitive sequences in the human genome (data not shown). The 905-28 cDNA identified single-copy sequences that are situated approximately 55 kb proximal to *FUR* (Fig. 1A).

The 905-28 cDNA then was used to screen a HeLa cDNA library. Twenty eight cDNAs were isolated, representing at

least 15 distinct classes of overlapping clones. Each of these classes had the same sequence as the 905-28 cDNA at their 3′ ends but a different length of 5′ sequence. In the longest cDNA isolated, clone H1, a long reading frame was found that was open to the 5′ end. Additional sequences upstream of the start of the H1 cDNA were identified by a PCR cloning method (see above). Clones extending 5′ of the H1 cDNA were isolated from the HeLa library, permitting the identification of 4,437 bp of sequence, which is referred herein as the H1-5′ sequence (Fig. 2).

Starting at the first in-frame ATG 74 bp from its 5′ end, the H1-5, sequence encodes a 1,417 amino acid peptide with a predicted molecular weight of 159 kDa. No in-frame stop codons were present between this ATG and the 5′ end of the H1-5′ sequences. An extensive cDNA analysis was carried out to map the 5′ end of the candidate gene. 8×10^6 LCL cDNA clones were screened by hybridization with a 5′ probe. Eleven clones were isolated, and their 5′ ends were sequenced (Fig. 3). In addition, 12 fibroblast clones prepared by a 5′ rapid amplification of cDNA ends (RACE) technique were sequenced. Both analyses indicated that the H1-5′ sequence is full-length.

The predicted peptide encoded in the H1-5′ sequence was used to carry out a BLASTP search of amino acid sequence databases. The searches identified significant homologies to motifs present in the three known peptides in the RecQ subfamily of DExH box-containing helicases (Fig. 4). The amino acid identities were concentrated in the region (residues 649 to 1041) containing the seven conserved helicase domains of the human *RECQL* (49%), *S. cerevisiae SGS1* (46%), and *E. coli recQ* (42%) genes. This suggests that the product of the candidate gene is a DNA helicase.

The seven helicase domains identified by their homology to RecQ constitute only the middle third of the predicted peptide. Between residues 588 and 661, amino acid

identities were discovered with three short motifs present in a broad phylogenetic spectrum of RNA polymerase II largest subunits (marked by asterisks in Fig. 2). The function of these motifs is unknown. No other significant homologies were identified to amino acid sequences in databases.

The amino-acid composition of the non-helicase regions of the predicted peptide is unusual. The amino-terminal 648 residues of the peptide are rich in acidic (17%), basic (12%), and polar (34%) amino acids; 13% of the residues are serines. Similarly, the carboxy-terminal 376 residues also are rich in acidic (11%), basic (16%), and polar (30%) amino acids; and again, 14% of the residues are serines. The function of these highly charged regions is unknown.

C. RNA Expression of the Candidate Gene in Cultured Cells

Northern blot analysis was used to determine the size of the full-length transcript from the candidate gene. The H1 cDNA was hybridized to total RNAs prepared from HeLa cells, normal diploid cultured fibroblasts, and non-BS LCLs. Two RNA bands at approximately 4.5 kb were visualized on the autoradiogram (Fig. 5A). This size is consistent with the length of the longest cDNAs sequenced (Fig. 2 and 3).

In addition, Northern blot analysis was performed using total RNAs prepared from LCLs from seven unrelated persons with BS (Fig. 5B). In three BS LCLs the quantity of RNAs identified by hybridization to the H1 cDNA was decreased in comparison to that of the control LCLs. In the other four BS LCLs the pattern of RNA mobilizes is aberrant: in one the upper band is missing, in another the lower band is missing, and in remaining two the ratio of the two RNA bands was reversed compared to that in normal cells; i.e., the intensity of the lower of the two bands was increased and the upper decreased in the BS LCLs. The RNA loading was equal in

all the lanes as evidenced by hybridization with a probe for the G3PD6 (glyceraldehyde-3-phosphate-dehydrogenase) gene. These observations suggest that RNAs identified by the H1 cDNA might be destabilized in BS LCLs as result of mutations in the candidate gene (see Surdej, P., et al. Ann. Rev. Genet. 28:263-282 (1994)).

D. Mutations in the Candidate Gene in Persons With BS

To determine whether the candidate gene is *BLM*, RNAs were prepared from LCLs from 13 unrelated persons with BS and from cell lines from 4 unaffected controls. These RNAs were used to generate cDNAs for mutational analysis of the expressed sequences of the candidate gene. Sequences in these 13 BS and 4 control non-BS cDNAs were amplified in approximately 200-bp segments using PCR primers designed from the open reading frame in the H1-5′ sequence (Table 2). The amplified segments were analyzed by single strand conformation polymorphism (SSCP) analysis using two conditions for electrophoresis. Novel SSCP conformers (Fig. 6) were identified, and the genetic changes underlying them were sequenced (Table 1).

Seven unique mutations were identified in 10 persons with BS (the boxed and diamond-marked nucleotides in Fig. 2), as well as four polymorphic base pairs which will not be described here. Four of the mutations introduced premature nonsense codons into the coding sequence, and three introduced amino acid substitutions (see below). One of the four chain-terminating mutations arose by a 3-bp deletion, one by a nucleotide substitution, one by a 1-bp insertion that caused a frameshift, and one by a 6-bp deletion accompanied by a 7-bp insertion that also caused a frameshift. This last mutation was detected in all four persons with Ashkenazi Jewish ancestry. The potential products encoded in these four mutant alleles are 185, 271,

515, and 739 amino acids in length, respectively, and none contains a complete set of the 7 helicase domains. Three of these mutant alleles were detected in the homozygous state, indicating that the persons inheriting them in double dose probably have no active *BLM* gene product in their cells. These observations are evidence that the H1-5′ sequences are mutated in persons with BS, thereby proving that the candidate gene is *BLM*.

Finally, two putative missense mutations were identified in two persons with BS that introduced amino acid substitutions at residues conserved in RecQ helicases (residues with asterisks in Fig. 4), and one was identified that introduced an amino acid substitution of cysteine to serine in the C-terminal region of the peptide. Because the three genetic alterations could be polymorphisms and the actual BS-associated mutations could have gone undetected, analyses of the *BLM* gene product *in vitro* will be required to demonstrate whether these substitutions cause the mutant phenotype.

III. Discussion

In the present study, *BLM* was isolated by a positional cloning strategy. *BLM* first was localized by homozygosity mapping to a 2-cM interval flanking *FES* (German, et al., 1994, supra), a gene already mapped to chromosome band 15q26.1. A 2-Mb YAC and P1 contig encompassing *FES* was constructed, and closely spaced polymorphic DNA markers in the contig were identified (Straughen, et al., supra). BLM then was assigned by SCP mapping to a 250-kb interval in the contig, one bounded by the polymorphic loci *D15S1108* and *D15S127* (Fig. 1). A cDNA clone (905-28) was isolated by direct cDNA selection using a cosmid clone from the interval, and cDNA analysis identified the 4,437-bp H1-5′ sequence (Fig. 2). This sequence encodes a putative peptide homologous to the RecQ helicases (Fig. 4). RNA transcripts

4.5-kb long were identified by Northern blot analysis (Fig. 5A), and electrophoretic abnormalities in RNAs were detected in cells from seven unrelated persons with BS, suggesting that these RNAs are derived from mutant *BLM* genes (Fig. 5B). Finally, RT-PCR/SSCP analysis disclosed 7 unique mutations in 10 persons with BS (Table 1; Fig. 6), 4 that are chain-terminating and 3 that are putative missense substitutions, 2 of the 3 affecting amino acid residues conserved in RecQ helicases and the third changing a cysteine to a serine.

A. SCP Mapping, a Powerful New Strategy

In a recent tabulation of the 42 inherited disease-associated genes isolated by positional cloning (Collins, F. Nature Genetics 9:347-350 (1995)) 19 were transmitted as autosomal dominants and 17 as X-linked recessives; however, only 5 were autosomal recessives. The reasons for the paucity of positionally cloned autosomal recessive disease-associated genes are at least twofold. First, the cloning of over half of the genes (26 of the 42 tabulated) was aided by chromosome breakpoints within or near the disease-associated gene; however, only one of these was in an autosomal recessive. Secondly, and of greater importance, the number of families transmitting rare autosomal recessive disease-associated genes generally is small, and the number of persons in sibships who would be informative in recombinational analysis also is small. Because a single investigator usually cannot obtain the numbers of families required for linkage analysis, the localization and subsequent positional cloning of rare autosomal recessive genes has lagged behind that of dominant and X-linked recessive genes.

Even when samples from numerous families have been collected and analyzed, usually the amount of positional information obtained is limited. In the case of BS, the

Bloom's Syndrome Registry (German and Passarge, supra), a research resource that has provided the material for all of the inventors' recent genetical studies, made possible an extensive recombinational analysis of *BLM* by homozygosity mapping. This analysis permitted a minimum regional assignment of *BLM* to approximately 1.4 Mb (unpublished results). This size of minimum interval is typical of recombinational analysis. A search for and subsequent mutational analysis of genes from a 1.4-Mb region would have been laborious.

The problem of too little positional information in available families can be mitigated in exceptional situations in which linkage disequilibrium between the disease-associated gene and tightly-linked polymorphisms can be detected in a genetic isolate. In these cases localization of a gene to a short interval in the genome by haplotype analysis can be more exact than is possible using standard linkage analysis of family data (e.g., Kerem, B.-S., et al. Science 245:1073-1080 (1989); Sirugo, G., et al. Am. J. Hum. Genet. 50:559-566 (1992); Lehesjoki, A. E., et al. Hum. Mol. Genet. 2:1229-1234 (1993); Hastbacka, J., et al. Cell 78:1073-1087 (1994)). Linkage disequilibrium in fact was a strategy available in BS (Ellis, et al., Am. J. Hum. Genet., 1994, supra), and it permitted a minimum regional assignment of *BLM* to the same 250-kb interval described herein (Ellis, et al., Linkage-disequilibrium mapping permits assignment of the Bloom's syndrome gene *BLM* to a 250-kb genomic DNA segment on chromosome 15. Genomics, submitted). This approach could have allowed the inventors to clone *BLM*. Instead, the inventors carried out SCP mapping first.

In the SCP-mapping strategy, the inventors took advantage of recombinant cell lines from BS somatic cells in which crossing-over within *BLM* had taken place, resulting in the correction of the mutant phenotype in their progenies (Ellis, et al., Am. J. Hum. Genet., 1995, supra). After a

segregational event, all polymorphic loci distal to *BLM* were reduced to homozygosity in half of the cases of intragenic recombination. This mapping method was preferred to linkage-disequilibrium mapping because the crossovers that permitted localization of *BLM* had occurred within the gene itself and fewer genotypes were required for the analysis. By genotyping polymorphic loci that flank *BLM* in high-SCE and low-SCE samples from only five persons with BS and their parents, the position of *BLM* was delimited to the short interval bounded by the marker loci *D15S1108* and *D15S127* (Fig. 1). With *BLM* assigned to such a short interval the cloning of *BLM* became straightforward. The first candidate gene isolated from the interval proved to be *BLM*.

B. Loss-of-Function Mutations at BLM

The candidate gene for *BLM* isolated from the interval identified by SCP mapping encodes a 1,417 amino acid peptide, previously unrecognized but homologous to RecQ helicases. Mutational analysis of the first 13 unrelated persons with BS examined permitted the identification of 7 unique mutations in 10 of them (Table 1). The fact that four of the seven mutations characterized so far result in premature termination of translation indicates that the cause of most BS is the loss of enzymatic activity of the *BLM* gene product. Identification of loss-of-function mutations in *BLM* (Table 1) is consistent with the autosomal recessive transmission of BS, and the homology of *BLM* and RecQ suggests that BLM has enzymatic activity. Thus, it is predicted that most BS mutations result in loss of function of BLM.

This loss of enzymatic activity is not lethal in cells, because three of the chain-terminating mutations were detected in a homozygous state. The non-lethality could result from the existence of some residual enzymatic activity in the truncated peptides; however, this seems unlikely because one of the homozygous chain-terminating mutations

results in chain termination after only 185 amino acids in a person with typical BS. Alternatively, the function of BLM may not be essential for cell survival. Other factors in the cell may be able to substitute for BLM, albeit inefficiently.

In the four persons with Jewish ancestry, a 6-bp deletion/7-bp insertion at nucleotide 2,281 was identified and each of the four persons was homozygous for the mutation. Homozygosity was predictable because linkage disequilibrium had been detected in Ashkenazi Jews with BS between *BLM*, *D15S127*, and *FES* (Ellis, et al., Am. J. Hum. Gen., 1994, supra). Thus, a person who carried this 6-bp deletion/7-bp insertion was a founder of the Ashkenazi Jewish population, and nearly all Ashkenazi Jews with BS inherit the mutation identical by descent from this common ancestor. Identification of the mutation now permits the screening of carriers in the Ashkenazim by a simple PCR test.

BS is an autosomal recessive with high penetrance and expressivity. The observation of loss-of-function mutations in *BLM* helps to explain these genetic characteristics. The short stature, characteristic facies, facial sun-sensitivity, hyper- and hypopigmented patches on the skin, immunodeficiency, male infertility, female subfertility, premature menopause, and the predispositions to late-onset diabetes and to neoplasia exist in virtually all groups of persons with the syndrome. The BS phenotype is similar in the Ashkenazi Jews, the Dutch, Flemish, German, Italian, Greek, Turkish, and Japanese -- i.e., wherever it's been diagnosed. In addition, the elevated chromatid exchange and the hypermutability are constant cellular manifestations. No more variability in the expressivity of the mutations has been detected in persons with BS who inherit an identical mutation by descent from a common ancestor, as happens in Ashkenazi Jews with BS and in the 25% of non-Ashkenazi Jewish persons with BS whose parents are cousins, than has been detected in persons who are compound heterozygotes (German et

al., 1995, supra). Nevertheless, with *BLM* cloned, it is possible to identify the mutations in any person with BS, and more subtle genotype-phenotype correlations now can be carried out.

C. BLM as a Putative DNA Helicase

The *BLM* gene product has been shown to be homologous at the amino acid level to the RecQ helicases (Fig. 4), a subfamily of DExH box-containing DNA and RNA helicases. *RecQ* is an *E. coli* gene which is a member of the RecF recombination pathway (Nakayama, H., et al. Mol. Gen. Genet. 195:474-480 (1984)), a pathway of genes in which mutations abolish the conjugational recombination proficiency and UV-resistance of a mutant strain lacking both the RecBCD (part of exonuclease V) and the SbcB (exonuclease I) activities (Horii, Z., and Clark, A. J. J. Mol. Biol. 80:327-344 (1973)). RecQ has DNA-dependent ATPase and DNA helicase activities and can translocate on single-stranded DNA in a 3′-5′ direction (Umezu, K., et al. Proc. Natl. Acad. Sci. USA 87:5363-5367 (1990)). Besides *BLM*, only two other *recQ*-like genes are known. First, *SGS1* is a yeast gene in which mutations suppress the slow growth of cells carrying mutations in the *TOP3* topoisomerase gene (Gangloff, S., et al. Mol. Cel. Biol. 14:8391-8398 (1994)). It also was isolated in a yeast two-hybrid screen through its interactions with both the yeast Top2 and Top3 topoisomerases (Gangloff, et al., supra; Watt, P. M., et al. Cell 81:253-260 (1995)). Secondly, *REQL* is a human gene isolated from HeLa cells the product of which possesses DNA-dependent ATPase, DNA helicase, and 3′-5′ single-stranded DNA translocation activities (Puranam, K. L., and Blackshear, P. J. J. Mol. Biol. 47:29838-29845 (1994); Seki, M., et al. Nucl. Acids Res. 22:4566-4573 (1994)). The homology of BLM with RecQ and RECQL strongly suggests that BLM also has DNA-dependent

ATPase and DNA helicase activities, and studies to investigate this have been initiated.

In addition to helicase domains, BLM contains N-terminal and C-terminal regions that are composed predominantly of charged and polar amino acid residues. The presence of non-helicase regions in BLM raises the possibility of additional enzymatic activities. The non-helicase regions could operate to provide functional specificity to BLM, e.g., by promoting interactions with other proteins, or could provide substrates for phosphorylation that might regulate BLM activity in the cell cycle.

D. A Function for BLM in DNA Replication

Some genes in the DExH family have been implicated in DNA repair, and mutations in three of them, the *XPB*, *XPD*, and *ERCC6* genes, have been identified in the human disease phenotypes xeroderma pigmentosum and Cockayne's syndrome (Weber, C. A., et al. EMBO J. 9:1437-1447 (1990); Frejter, W. L., et al. Proc. Natl. Acad. Sci. USA 89:261-265 (1992); Troelstra, C., et al. Cell 71:939-953 (1992); Sung, P., et al. Nature 365:852-855 (1993); Ma, L., et al. Mol. Cell. Biol. 14:4126-4134 (1994)). A universal function for the RecQ helicases, however, is not established. No abnormality in humans has been attributed to defects in *RECQL*. Even the cellular function of RecQ in bacteria is unclear, although it most likely participates in an aspect of post-replication recombinational repair (Luisi-DeLuca, C., et al. Genetics 122:269-278 (1989); Kusano, K., et al. Proc. Natl. Acad. Sci. USA 91:1173-1177 (1994); Tseng Y.-C., et al. Mutation Res. 315:1-9 (1994)). The phenotype of yeast *SGSI* mutants includes slow growth, poor sporulation, chromosome nondisjunction at mitosis, missegregation in meiosis (Watt, et al., supra), and an elevated recombination frequency (Gangloff, et al., supra). SGS1 is known to interact with

topoisomerases II and TOP3, and therefore may function in chromosome separation, a process in which intertwined DNA strands are resolved when replication forks converge. The predicted sizes of BLM (1,417 residues) and SGS1 (1,447 residues) are similar, the two peptides have similar base-compositions outside the helicase domains, and mutations in the genes encoding them result in genomic instability. In addition, an interaction between BLM and topoisomerase II in human cells has been suggested by the observation that topoisomerase II activity is decreased in BrdU-treated BS cells (Heartlein, M. W., et al. Exp. Cell Res. 169:245-254 (1987)). Although these interesting similarities are inconclusive, the possible functional homology between BLM and SGS1 warrants further investigation.

In general, BLM has been implicated in the complex processes of DNA replication. Mutations in *BLM* have impressively pleiotropic cytogenetic and biochemical consequences. The chromosome breaks, gaps, and translocations and the high frequency of intra- and interchromosomal strand exchanges all point to a disturbance of DNA replication. In BS cells, the rate of nascent DNA chain-elongation is retarded (Hand, R., and German, J. Proc. Natl. Acad. Sci. U.S.A. 72:758-762 (1975); Giannelli, F., et al. Nature 265:466-469 (1977)), and the distribution of DNA replicational intermediates is abnormal (Lonn, U., et al. Cancer Res. 50:3141-3145 (1990)). Some though not all cultured BS cells exhibit increased sensitivity to DNA-damaging agents, e.g. UV radiation, mitomycin C, N-nitroso-N-ethylurea, and ethyl methanesulfonate (Krepinsky, A. B., et al. Hum. Genet. 50:151-156 (1979); Krepinsky, A. B., et al. Mutation Res. 69:357-368 (1980); Ishizaki, K., et al. Mutation Res. 80:213-219 (1981); Heddle, J. A., et al. (1983) Cellular sensitivity to mutagens and carcinogens in the chromosome-breakage and other cancer-prone syndromes. In Chromosome Mutation and Neoplasia, J. German, ed. (Alan R.

Liss, Inc., New York), pp.203-234; Kurihara, T., et al. Mutation Res. 184:147-151 (1987)). Disturbances in several enzymes that participate in DNA replication, DNA repair, or both have been identified in some though, again, not all BS cell lines, including DNA ligase I (Chan, J.Y.H., et al. Nature 325:357-359 (1987); Willis, A. E. and Lindahl, T. Nature 325:355-357 (1987)), topoisomerase II in BrdU-treated BS cells (Heartlein, et al., supra), thymidylate synthetase (Shiraishi, Y., et al. Mutation Res. 211:273-278 (1989)), uracil DNA glycosylase (Seal, G., et al. Proc. Natl. Acad. Sci. U.S.A. 85:2339-2343 (1988)), N-methylpurine DNA glycosylase (Dehazya, P., and Sirover, M. A. Cancer Res. 46:3756-3761 (1986)), O^6-methylguanine methyltransferase (Kim, S., et al. Mutation Res. 173:141-145 (1986)), and superoxide dismutase (Nicotera, T. M., et al. Cancer Res. 49:5239-5243 (1989)). These investigations show that certain enzymes concerned with DNA replication and, or, repair appear to be dysregulated in BS and that cultured BS cells make variously abnormal responses to DNA-damaging agents.

The evidence that BS cells have a defect in DNA repair, however, is slight (Friedberg E. C., et al. Adv. Rad. Biol. 8:85-174 (1979); German, J, and Schonberg, S. (1980) Bloom syndrome. IX. Review of cytological and biochemical aspects. In Genetic and Environmental Factors in Experimental and Human Cancer, H. V. Gelboin, B. MacMahon, T. Matsushima, T. Sugimura, S. Takayama, and H. Takebe (eds.) (Japan Scientific Societies Press, Tokyo) pp 175-186). BS cells are not hypersensitive to UV or X-ray irradiation by standard assays, and no defect in a specific DNA-repair enzyme or pathway has been reported. Although the explanation for the pleiotropic effects of BS mutations still is unknown, the predicted function of BLM as a DNA helicase implies that the BS cell encounters greater difficulties than the normal in the resolution of specific DNA structures generated during DNA replication. BLM presumably is one member of an assembly

of gene products that acts in a pathway to resolve these structures. The excessive rates of chromatid exchange (homologous chromatid interchange configurations at metaphase and the SCE rates) might be microscopically visible manifestations of repair processes that are activated by the mutant cell's inability to resolve the structures properly. Identification of the substrates on which BLM operates represents one of the important areas for future investigation.

IV. Conclusions

With the cloning of the *BS* gene and the inference that its gene product is a DNA helicase, new insight has been gained into the molecular basis of the genomic instability which is the most impressive feature of BS cells. The absence of the *BLM* gene product most likely destabilizes other enzymes that participate in DNA replication and repair, perhaps through direct interactions or through more general responses to DNA damage. Elucidation of the enzymatic activities of BLM, the factors with which it interacts, and the substrates on which it operates now are required in order to understand the role of BLM in the maintenance of genomic stability, and may play a role in cancer diagnosis and therapy in the population at large.

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Table 1. Mutations identified in the candidate gene in persons with Bloom's syndrome.

Person			Mutation					
I.D.[a]	Ancestry	Cell line	Position[b] (bp)	Alteration[c]	Zygosity at *BLM*[d]	Kind	Codon change	Predicted peptide[e]
97(AsOk)	Japanese	HG1926	631	3-bp del[f]	Homo	Nonsense	S→stop	185
112(NaSch)	German	HG2510	888	A→T	Hetero	Nonsense	K→stop	271
93(YoYa)	Japanese	HG1626	1610	1 bp ins	Homo	Frameshift[g]		515
139(VlKre)	American/European	HG2231	2089	A→G	Hetero	Missense	Q→R[g]	1417
15(MaRo)	Ashkenazi Jewish	HG1514	2281	6 bp del/ 7 bp ins	Homo	Frameshift[i]		739
42(RaFr)	Ashkenazi Jewish	HG2522	2281	6 bp del/ 7 bp ins	Homo	Frameshift[i]		739
107(MyAsa)	Ashkenazi Jewish	HG2654	2281	6 bp del/ 7 bp ins	Homo	Frameshift[i]		739
NR2(CrSpe)	Ashkenazi Jewish	HG2727	2281	6 bp del/ 7 bp ins	Homo	Frameshift[i]		739
92(VaBl)	Italian	HG1584	2596	T→C	Homo	Missense	I→T[j]	1417
113(DaDem)	Italian	HG1624	3238	G→C	Homo	Missense	C→S[k]	1417

[a] Bloom's Syndrome Registry designations. Three unrelated persons with BS were examined in whom mutations have yet to be detected: 61(DoHo), in HG2122; 30(MaKa), in HG1987; 140(DrKas), in HG1972.

[b] The nucleotide positions are as identified in the H1-5' sequence (Fig. 2).

[c] Del, deletion; ins, insertion.

[d] Homo, homozygous; hetero, heterozygous.

[e] Number of amino acids starting from the first in-frame ATG found in the H1-5' sequence (Fig. 2).

[f] The deletion of CAA at nucleotide positions 631-633 results in a stop codon at amino acid position 186 (Fig. 2).

[g] The insertion of an A bp causes the insertion of a novel codon for K after amino acid 514 position (taken from the H1-5' sequence, Fig. 2), and after this codon there is a stop codon.

[h] At amino acid position 672.

[i] The deletion of ATCTGA and insertion of TAGATTC causes the insertion of the novel condons for LDSR after amino acid position 736, and after these codons there is a stop codon.

[j] At amino acid position 843.

[k] At amino acid position 1055

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Table 2. Pairs of primer sequences used for SSCP analysis of *BLM*.

Name	Forward sequence[a]	Reverse sequence[a]	Product length (bp)
C1-B	GGATCCTGGTTCCGTCCGC	GAGGTTCACTGAAGGAAAAGTC	269
C1-A	CAACTAGAACGTCACTCAGCC	GAAGTCCTTGACCCTTTGCTG	233
C1-1	GACTTTTCCTTCAGTGAACCTC	GGGATTTCTTTACAGTTGGTGTG	186
C1-2	CCAGATTTCTTGCAGACTCCG	CTCTTACAAAGTGACTTTGGGG	213
C1-3	CTTTAAGTACCATCAATGATTGGG	CCTCAGTCAAATCTATTTGCTCG	227
C1-4	GAGTAAGCACTGCTCAGAAATC	GCTTAACCATTCTGAGTCATCC	160
C1-5	CGAGCAAATAGATTTGACTGAGG	CAATACATGGAACTTTCTCAGTTG	223
C1-6	GAAGATGCTCAGGAAAGTGAC	CGTACTAAGGCATTTTGAAGAGG	215
C1-7	CAACTGAGAAAGTTCCATGTATTG	CACAGTCTGTGCTGGTTTCTG	239
C1-9	CTATTCCTGATGATAAACTGAAAC	CCTTCATAGAATTCCCTGTAGG	200
C1-10	GTGGAGATACAGGCCTGATTC	GTGTTTCAGCCCAGTTGCTAC	244
C1-11	CAGGATTCTCTGCCACCAGG	GCAGTATGTTTATTCTGATCTTTC	183
C1-12	CAGGAAATGTTCTCACAAGCAC	CCTTGATGGGTTGATAGGCAG	203
C1-13	CAGCCAGCAAATCTTCCACAG	CGCTCATGTTTCAGATTTCTGG	204
C1-14	GAATTATACTGACAAGTCAGCAC	GATCTACGATAAGTGATCTCAAG	295
C1-15	CTCCTGGGGTCACTGTTGTC	GAGTCTGTTACTTGCACAGATC	211
C1-16	CAATCATAAAACTTCTATATGTCAC	GCCATCACCGGAACAGAAGG	207
C1-17	GTGGGGACATGATTTTCGTCAAG	GATTATGTCTGTTAAAGCTCATG	175
C1-18	GACATCCTGACTCAGCTGAAG	CGTGTCAGCCATGGTGTCAC	203
C1-19	GCACCACCCATATGATTCAGG	CAGATAACC TGA CAGCCATCC	179
C1-20	GATGAAGTGCAGCAGAAGTGG	CAGTCTGGTCACATCATGATAG	221
C1-21	GCAGAGCTGGAAGAGATGGG	GCTGTATTCTCCTGCATTCCG	188
C1-22	GTATAGCATGGTACATTACTGTG	CCTTGTGATGAACTATGTTCTTG	228
C1-23	GACTGACGATGTGAAAAGTATTG	CCAAAATCTTGTCAAGTATCAGC	235
C1-24	CCAGTCAGGTATATTTGGAAAAG	GGAATTTTCTGTTTCCATAAAGTC	206
C1-25	CGATCGCTTATGTGATGCTCG	CAAGCTTCTTGAGAGTGACGG	248
C1-26	GAACTTACAGAAGTCTGCAAATC	GATGTCCATTCAGAGTATTTCTG	208
C1-27	GGTGTTACTGAAGACAAACTGG	GGGTATTTCCTCGTCAAGCTC	168
C1-28	GGATAAGCCTGTCCAGCAGC	CCTAGATATCTTTCTACATGTGG	214
C1-29	GCTTCCAGTGGTTCCAAGGC	GTTATGAGAATGCATATGAAGGC	204
C1-30	CTCAAGCGACATCAGGAGCC	CAAGAATAACAGCTTTATAGTCAC	178

[a] 5' to 3'

All publications mentioned hereinabove are hereby incorporated by reference in their entirety.

While the foregoing invention has been described in some detail for purposes of clarity and understanding, it will be appreciated by one skilled in the art from a reading of the disclosure that various changes in form and detail can be made without departing from the true scope of the invention in the appended claims.

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